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Do peat amendments to oil sands wet sediments affect *Carex aquatilis* biomass for reclamation success?

Marie-Claude Roy [a,*], Federico P.O. Mollard [a,b], A. Lee Foote [a,c]

[a] Department of Renewable Resources, University of Alberta, Edmonton, Alberta T6G 2H1, Canada
[b] Departamento de Biología Aplicada y Alimentos, FAUBA, C1417DSE Buenos Aires, Argentina
[c] Devonian Botanic Garden, Edmonton, Alberta T6G 2E1, Canada

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ABSTRACT

The oil sands industries of Alberta (Canada) have reclamation objectives to return the mined landscape to equivalent pre-disturbance land capability. Industrial operators are charged with reclaiming a vast landscape of newly exposed sediments on saline-sodic marine-shales sediments. Incorporated in these sediments are by-products resulting from bitumen extraction (consolidated tailings (CT), tailings-sand (TS), and oil sands processed water (OSPW)). A sedge community dominated by *Carex aquatilis* was identified as a desirable and representative late-succession community for wet-meadow zones of oil sands-created marshes. However, the physical and chemical conditions, including high salinity and low nutrient content of CT and TS sediments suppress plant growth and performance. We experimentally tested the response of *C. aquatilis* to amendments with peat-mineral-mix (PM) on oil sand sediments (CT and TS). In a two factorial design experiment, we also tested the effects of OSPW on *C. aquatilis*. We assessed survival, below- and aboveground biomass, and physiology (chlorophyll *a* fluorescence). We demonstrated that PM amendments to oil sands sediments significantly increased *C. aquatilis* survival as well as below and aboveground biomass. The use of OSPW significantly reduced *C. aquatilis* belowground biomass and affected its physiological performance. Due to its tolerance and performance, we verified that *C. aquatilis* was a good candidate for use in reclaiming the wet-meadow zones of oil sands-created marshes. Ultimately, amending CT and TS with PM expedited the reclamation of the wetland to a *C. aquatilis*-community which was similar in gross structure to undisturbed wetlands of the region.

1. Introduction

In the Fort McMurray region of northern Alberta, Canada, the surface mineable area available to the oil sands industry is approximately 4800 km^2 (Government of Alberta, 2013). Currently 1670 km^2 of the mineable surface has either been mined or approved for development within the next decades (Government of Alberta, 2013). The oil sands region of Alberta is located in the north-west part of the boreal region of Canada (see Brandt, 2009) for an overview of the North American boreal zone). The undisturbed land of this region is formed by a mosaic of uplands (varying from aspen-dominated deciduous forest to spruce–fir–pine-dominated conifer forests) and wetlands communities (bogs, fens, marshes) adapted to long, cool winter and short, cool summers (Vitt and Bhatti, 2012). Of the mineable landscape, 63% originally supported wooded fen vegetation and 3% supported marsh vegetation (Raine et al., 2002; Rooney et al., 2012). Despite the low abundance of marshes relative to fens and bogs in this area, a marsh community has been identified as the best endpoint for the reclamation of wetlands under the challenging conditions of the post-mined landscape (e.g. mineral substrate, elevated water and sediment salinity, residual petroleum) (Purdy et al., 2005).

Studies of plant primary succession of sand extraction pits in Siberia, (Koronatova and Milyaeva, 2011) and insect occupancy of quarries in Central Europe (Heneberg et al., 2013) showed distinct succession patterns and rapid natural contributions to on-site species richness. They make a convincing arguments that post-mining sites respond to catenal, abiotic, and annual weather patterns to supplement regional species diversity. Similar processes are likely at work in the oil sands post-mined landscape, albeit at lower levels due to the continuously increasing distance to natural source areas and the post-mined physical and chemical conditions.

* Corresponding author. Department of Renewable Resources, University of Alberta, 751 GSB, Edmonton, Alberta T6G 2H1, Canada. Tel.: +1 780 492 8743.
E-mail addresses: roy4@ualberta.ca (M.-C. Roy), fmollard@agro.uba.ar (F.P. O. Mollard), leefoote@ualberta.ca (A.L. Foote).

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Goals of maximizing diversity are valuable but secondary to rapidity of establishing the stabilizing influence of plant cover in the post-mined landscape. Although there are missed opportunities in the boreal forest to allow primary succession in mine-disturbed areas to serve as hotspots of plant and insect diversity (Kareiva and Marvier, 2003; Koronatova and Milyaeva, 2011; Heneberg et al., 2013), Alberta's reclamation policy and guiding regulations require as rapid a return to representative regional condition for wetlands as possible (Harris, 2007; Government of Alberta, 2013). While abundant open area remains for natural colonization, government policy in oil sands encourages technical reclamation to expedite soil stabilization, carbon accumulation and functions as similar regional mature wetlands as possible (Harris, 2007).

In the wet-meadow zone of natural marshes in this region, *Carex* sp. represents more than 70% of the total macrophyte aboveground biomass (Roy and Foote, unpublished data). A sedge-community dominated by *C. aquatilis* was identified by Raab and Bayley (2013) as the optimal target community that constituted successfully reclaimed marshes. In addition to providing plant composition and function in the oil sands mined landscape that are similar to local undisturbed marshes, *C. aquatilis* is a promising species for reclamation due to its ability to spontaneously colonize (Prach et al., 2011) during the early development of certain oil sands created marshes (Roy and Foote unpublished data) and to tolerate pollution (Mollard et al., 2012). The sedge-community of natural marshes is dominated by the cover and biomass of *C. aquatilis, Carex utriculata and Carex atherodes* and *a* sub-community composed of *Scutellaria galericulata*, *Polygonum amphibium*, and *Galium trifidum* for example (Raab and Bayley, 2013; Roy and Foote, unpublished data). In oil sands created marshes where a sedge-community is present, the cover is dominated by only one species of *Carex* (i.e. *C. aquatilis*) and a sub-community composed *Achillea sibirica*, and *Melilotus* spp. for example (Raab and Bayley, 2013; Roy and Foote, unpublished data). In certain oil sands marshes, *C. aquatilis* occurs in very low abundance or is absent and the wet-meadow community is dominated by species such as *Typha latifolia* that are atypical of natural marshes (Roy and Foote, unpublished data). Thus, if early plant cover in the wet-meadows of oil sands created marshes is desired, the early planting of *C. aquatilis* appears to be a possible solution to dispersal limitation and to pre-empt the establishment of less desirable plant species (Raab and Bayley, 2013). In certain oil sands marshes *C. aquatilis* percent cover was similar to natural marshes, however, *C. aquatilis* aboveground biomass was significantly lower (Raab and Bayley, 2013). This difference was tentatively attributed to the toxic content of oil sands reclamation materials, the low nutrient availability, and reduced organic matter content of newly created marsh sediments (Trites and Bayley, 2009; Giesy et al., 2010; Rooney and Bayley, 2011).

At the individual plant level, *C. aquatilis* growth and performance were reduced in oil sands marshes compared to natural references (Mollard et al., 2012). The chemistry and structural characteristics of the oil sands processed materials (tailings sediments and waters) appeared to reduce plant growth and physiology (Mollard et al., 2012), thus slowing the rate of reclamation (Purdy et al., 2005; Mollard et al., 2012). Emergent macrophytes, such as *C. aquatilis*, constituted a major fraction of organic matter production in freshwater marshes and the decomposition of plant litter by microbial processes fuels the *in situ* energy flow and nutrient cycling (Malcom, 1990; Kuehn et al., 2000). Mining activities have resulted in massive loss of wetlands and stored carbon (Rooney et al., 2012). Carbon sequestration through peat accumulation, sediment deposition and plant biomass is a key function provided by North American wetlands (Bridgham et al., 2006). Wetlands' ability to sequester carbon has repercussions for the regional and global carbon dynamic and provides crucial services to society in the context of climate change (Zedler and Kercher 2005; Bridgham et al., 2006). Ensuring that *C. aquatilis* growing in the oil sands of Alberta have elevated biomass and consequently, increased litter production, similar to natural marshes of the region is one step toward successfully reclaiming wetland processes and functions (Purdy et al., 2005; Johnson and Miyanishi, 2008).

Wetland soils and sediments are critical and challenging component to reclaim (Bruland and Richardson, 2006). Organic matter amendment in newly restored marshes improves soil proprieties and ecosystem functions. The deliberate addition of organic matter in created wetlands has been the focus of numerous studies (e.g. Bailey et al., 2007; Sutton-Grier et al., 2009; Ballantine et al., 2012) however, its positive effects on community structure (i.e. richness and/or composition) and on macrophyte growth and physiology remains controversial (see Handa and Jefferies, 2000; O'Brien and Zedler, 2006). In oil sands created marshes, a peat-mineral mix (PM) that contains three to five times the amount of organic carbon found in consolidated-tailings (CT) and tailing-sand (TS) has been used to increase soil aeration, water retention, root penetration and microbial habitat (Brady and Weil, 2008) (Table 1). The amendment of created marshes with PM was also intended to buffer soil from strong pH fluctuations and remove contaminants from water by adsorption, sequestration and denitrification processes (Tsutsuki and Ponnamperuma, 1987; Craft et al., 1988; Hogan et al., 2004; Sutton-Grier et al., 2009; Harrison-Kirka et al., 2013). Saline marshes created using tailings sediments and freshwater then capped with PM and *Carex* sp. were observed to produce twice as much aboveground biomass (124.4 g/m^2) as similar created marshes not capped with PM (Roy and Foote, unpublished data). However, the limited number ($n = 4$) of these pilot marshes precluded strong conclusions about the benefits of organic matter amendment on plant biomass.

The oil sands created marshes are generally constructed using a variety of unusual sediment formulations resulting from the extraction and transformation of bitumen. Oil sands marsh creation occurs on the newly exposed marine–shale overburden (Purdy et al., 2005). Some of these oil sands created marshes are capped with processed materials produced during the bitumen extraction process such as CT, TS and oil sands processed water (OSPW). The CT is composed of sand, clay, and gypsum while TS is mainly composed of sand (Harris, 2007). Both, CT and TS contain moderate to elevated salinity levels, residual bitumen and associated hydrocarbon contaminants (Harris, 2007). Both CT and TS are low in organic matter. In addition to its chemistry, the density of CT has been hypothesized to reduce plant root penetration (Rooney and Bayley, 2011). Notably, OSPW is recycled many times through the extraction process, whereby it accumulates high levels of salts, naphthenic acids, and ions including ammonia (NH_4), chloride (Cl), boron (B), and copper (Cu) (MacKinnon et al., 2005; Giesy et al., 2010). The physical properties and chemistry of CT, TS and OSPW are likely to influence marsh vegetation and its functions (Crowe et al., 2002; Kamaluddin and Zwiazek, 2002; Kovalenko et al., 2013).

The PM was obtained during the top-soil removal preceding surface mining but its use in oil sands created marshes is expensive. In addition to its excavation, storage and transportation, stored PM is subjected to a period of rapid decomposition (oxidation) which leads to CO_2 release in the atmosphere (Bruland and Richardson, 2006). Furthermore, Sutton-Grier et al. (2009) found the richness of wetland species decreased with an increase of organic matter suggesting the possibility for non-generalizable or non-linear effects of organic matter amendment in created wetlands. Determining if PM enhances macrophyte functions in oil sands created marshes is thus important to guide successful reclamation

Table 1
Chemistry of consolidated-tailings (CT), tailings-sand (TS) and peat-mineral mix (PM) from which mixtures (i.e. CTPM and TSPM) were obtained. (TP = total phosphorus, NPOC = non-purgeable organic carbon, DC = dissolved carbon, DN = dissolve nitrogen, DOC = dissolved organic carbon, TC = total carbon, TN = total nitrogen, EC = electric conductivity, SM = sediment moisture).

Sediment types	Fe^{2+}	Mg^{2+}	Na^{+}	Cl^{-}	TP	NPOC	DC	DN	DOC	TC	TN	EC	SM
	mg/kg	mg/kg	mg/kg	mg/kg	mg/L	mg/L	mg/L	mg/L	mg/kg	mg/kg	mg/kg	us/cm	%
TS	1.3	30.4	814.9	1.1	0.0	27.8	44.5	0.6	37.2	59.4	0.8	306.2	25.8
CT	1.7	335.6	995.2	14.4	0.4	47.7	69.0	0.9	67.2	97.3	1.3	395.0	31.8
PM	2.4	480.3	4018.8	78.7	0.6	66.1	114.1	3.4	180.3	311.3	9.4	598.1	90.7

practices, validate key reclamation practice costs, while minimizing the related environmental costs. The post-mining oil sands landscape represents an ideal environment to test the effects of organic matter amendment on marsh vegetation functions in newly created wetlands.

The overall goal of this study is to determine if the addition of PM to oil sands sediments would enhance *C. aquatilis* biomass and metabolism. We studied the introduction of *C. aquatilis* and its short-term growth under the various post-mined conditions. Our three objectives were to: 1) characterize the plant response to two types of water (i.e. freshwater and OSPW) and three types of reclamation sediment (i.e. CT, TS and PM), 2) experimentally test the effects on plants resulting from PM addition to CT and TS, and 3) understand the effects of oil sands processed water (OSPW) on *C. aquatilis*.

2. Material and methods

2.1. Research site

This field study was conducted in the Fort McMurray region of Northeastern Alberta, Canada on *Suncor Energy Inc.* property (56°58′49.70″N and 111°30′22.45″W). Six parallel research trenches constructed in 1995 were used to conduct the experiment. Trenches were oriented in a north-south direction. Each trench was approximately 40 m long and 5 m wide and a distance of approximately 12 m separated them. During their construction, the trenches were capped with 10 cm of overburden on top of a synthetic membrane to prevent leakage. As many other wetlands created in the post-mined landscape, overburden was used as reclamation subsoil. Overburden is a natural soil that is salvaged below the organic surface soils (i.e. PM and upland surface soils) in advance of mining and either stockpiled or directly placed onto an area for reclamation. From 2005 to 2012, the trenches were used for research purposes and water levels and contents were kept constant by the repeated addition of OSPW in trenches 2, 4 and 6 and freshwater in trenches 1, 3 and 5. Based on measurements made in created and natural marshes of the Fort McMurray region, trench water levels were allowed to fluctuate during the summer within *a priori* set water level range (i.e. minimum of 2 cm and a maximum of 10 cm high) that would favor *C. aquatilis* growth. The trenches were periodically flushed or supplemented with their respective water treatment to account for water lost through evapotranspiration and to adjust solute concentrations. The OSPW used for the experiment was collected from a tailing pond water catchment basin, while freshwater was collected from an onsite constructed lake. The six trenches were assumed to be affected by similar environmental and climatic conditions characteristic of the Fort McMurray region. Mean summer and winter daily temperature averages of the region are 13.5 °C and −13.2 °C, respectively (Strong and Legga, 1992).

Table 2
Water chemistry components averaged ($n = 3$) and their associated ±CI (95%). (*) indicates significant differences between water treatments (F = freshwater, OSPW = oil sands process water).[a]

	F		OSPW	
	Average	CI	Average	CI
Temperature (°C)	18.0	1.1	17.8	0.9
Salinity (ppt)*	0.2	0.0	0.7	0.0
Oxidoreduction potential (mV)	95.5	10.1	85.0	17.4
pH	7.5	0.6	8.0	0.2
Dissolved oxygen (mg/l)	3.9	1.2	3.3	0.8
Naphthenic acid (ppm)*	3.0	0.0	22.7	3.5
Carbonates (CO_3^{2-}) (ppm)*	0.0	0.0	21.4	14.8
Bicarbonates (HCO_3^-) (ppm)*	239.0	51.1	598.3	85.4
Chlorides (Cl^-) (ppm)*	62.0	8.5	176.7	77.1
Sulfates (SO_4^{2-})*	90.1	3.4	174.0	58.2
Sodium (Na^+) (ppm)*	64.4	6.2	380.3	46.6
Magnesium (Mg^{2+}) (ppm)*	24.1	2.2	20.2	2.4
Calcium (Ca^{2+}) (ppm)*	59.8	20.0	36.4	1.5
Ammonium (NH^{4+}) (ppm)	0.3	0.1	0.3	0.0
Boron (B) (ppm)*	0.2	0.1	1.8	0.4
Manganese (Mn) (ppm)*	24.1	1.1	20.2	1.2
Silicon (Si) (ppm)	0.4	0.2	0.9	0.5
Sulfur (S) (ppm)*	32.6	1.3	65.1	20.1
Strontium (Sr) (ppm)	0.3	0.1	0.4	0.1

[a] To determine which water chemistry components were significantly different between water types, a PCA coupled with *t*-tests was performed. The PCA was used to express the covariation of the water chemistry components (17) as a smaller number of composite variables (2). Prior to the PCA analysis, data were log transformed and standardized. The trench scores in the reduced space were then used to perform *t*-tests.

2.2. Experimental design, data collection and statistical analyses

The PM addition was tested on CT and TS. The growth experiments were conducted under two factors being 1) sediment types (CT, CT and PM mixture (CTP), TS, TS and PM mixture (TSPM), and PM) and 2) water types (freshwater versus OSPW). The CTPM and the TSPM were composed of a mixture of 1/3 of processed material and 2/3 PM. The experiment was replicated three times (i.e. in three trenches). Thus, twelve treatments (i.e. six sediment combinations subjected to two water types) were tested. *A priori* power analyses were performed to calculate the total sample size needed to test the sediments × waters two-factor interaction at α level 0.05 and indicated a minimum power of 0.6. To increase the power of our analysis, CT and CTPM pots were compared to *a priori* selected PM pots (PM1) while TS and TSPM pots were compared to a different set of PM pots (PM2). Three unplanted control pots per sediment type were randomly placed in each trench to test for unanticipated plant invasion.

C. aquatilis plants were collected in June 2010 in a natural marsh of the Fort McMurray region (56°30′50, 31″N and 111°16′17, 47″W). All plants collected from the natural marshes were randomly transplanted in one gallon pots and the pots were randomly assigned to a position in the trenches during the same day. To ensure that the conditions (e.g. water level) were optimal for the transplanted *C. aquatilis*, the pots were located in the same zone of the trenches where naturally occurring *C. aquatilis* was growing.

Each week during the summer 2010 and 2011, trench water chemistry including temperature, pH, oxidative-reduction potential (ORP), salinity, dissolved oxygen (DO), and specific conductance (adjusted for temperature and hydrogen ions) were monitored using a Handheld Oxygen, Conductivity, Salinity, and Temperature System (YSI85) (Table 2). Once each summer, naphthenic acids, anions and cation levels were sampled by Suncor Energy Inc. and analysed by Syncrude Canada Ltd. Environmental lab. Bicarbonates and carbonates were analyzed by alkalinity titration, chlorides, sulfates and ammonium were analyzed by ion chromatography, while sodium, magnesium, calcium, boron, manganese, silicon, sulfur, and strontium were analyzed using an inductively coupled plasma optical emission spectrometry.

To test *C. aquatilis* stress level under each treatment, chlorophyll *a* fluorescence was used as a proxy for physiological performance. In August 2011, fluorescence measurements were carried out on *C. aquatilis* dark-adapted leaves in five pots of each soil and water treatment. The five measurements were then averaged for each replicate. Chlorophyll *a* fluorescence transients were measured with a Hansatech Pocket PEA (Hansatech Instruments Ltd., King's Lynn, Norfolk, UK). The definitions and derivations of the fluorescence transient parameters are summarized in Table 3 (for further details see Strasser et al., 2000).

At the end of the 2011 growing season each plant belowground biomass (roots and rhizomes) and aboveground biomass (culms and leaves) were harvested and individually stored in paper bags. The samples were brought to the lab and dried in the oven at 70 °C to a constant weight before they were weighed for biomass.

2.3. Statistical analysis

2.3.1. Data screening

Survival, biomass and chlorophyll *a* fluorescence data were inspected for outliers, normality, and homogeneity of variance prior to statistical analyses. Data with non-normal distributions were log transformed and data expressed as ratios were *arcsin* transformed.

2.3.2. C. aquatilis survival, biomass and physiology

Survival was first averaged in each of the eight pots of each treatment. Then, survival was averaged for the three replicated treatments. Biomass of surviving plants was collected in all eight pots in each treatment (i.e. CT, CTPM, PM1, TS, TSPM and PM2). Thus, the average biomass calculated per replicate represented the biomass produced by the remaining alive plants. Belowground mass ratio and aboveground mass ratio were defined as the ratio of belowground mass and aboveground mass, respectively, to the sum of below and aboveground biomass.

Two-way ANOVAs ($\alpha = 0.05$, $n = 3$) were performed to test whether 1) sediment and water treatments had an overall effect on *C. aquatilis* survival/biomass/fluorescence, and 2) the effect of sediment was the same under the two types of water (interaction of treatments). Where the F-ratio for the sediment or water treatment main effect was significant ($p < 0.05$), pairwise comparisons to isolate differences were performed using Tukey tests ($\alpha = 0.05$, $n = 3$). CT was only statistically compared to CTPM and PM1 while TS was always and only statistically compared to TSPM and PM2.

Table 3
Derivation of the parameters directly obtained from the recorded fluorescence transients.

Parameters	Derivation
$F_{0:}$ fluorescence at 50 μs; assumed to be initial	F_0
F_m: maximal fluorescence intensity	F_m
F_v: variable fluorescence	$F_v = F_m - F_0$
$M_{0:}$ slope at the origin of normalized fluorescence rise	$dV/dt_0 = (f\ 300\ \text{ms} - F_0/(F_m - F_0)$
ABS/RC: calculated absorption per reaction center[a]	$(M_0/Vj)/(1 - F_0/F_m)$
F_v/F_m: maximum quantum yield of primary photochemistry	$1 - F_0/F_m$
PI: Performance Index	$(V_j/M_0)(F_v/F_m)(F_v/F_0)(ET_0/(dQ_A/dt_0)$
$ET_0/TR_{0:}$ Probability that a trapped exciton moves an electron further than Q_A	$1 - V_j$
ET_0/ABS: Probability that an absorbed photon moves an electron further than Q_A	$(1 - F_0/F_m)(1 - V_j)$

[a] *Vj*: After Christen et al. (2007) and Strasser et al. (2000). $Vj = (F_2\ \text{ms} - F0)/(FM - F_0)$.

3. Results

3.1. C. aquatilis survival

In CT sediment types (CT, CTPM and PM1), only sediment types influenced *C. aquatilis* survival (Fig. 1, Table 4). *C. aquatilis* survival was significantly higher in freshwater and OSPW when growing in PM (PM1) than in either CT or CTPM. No sediment or water effects were found on *C. aquatilis* survival in TS sediment types (TS, TSPM and PM2). No overall effect was found from the interaction of sediment and water treatments for both CT and TS sediment types.

3.2. C. aquatilis biomass

In CT sediment types, sediment had a significant effect on both below and aboveground biomass ($p < 0.05$) (Fig. 2, Table 4). In OSPW plants had significantly higher biomass in CTPM and PM1 than in CT ($p < 0.05$). Plants growing in the CT/OSPW treatment had significantly lower below and aboveground biomass when compared to other treatments ($p < 0.05$). Despite the finding that plants growing in freshwater had a tendency to have higher biomass in CTPM and PM1 than in CT, the differences were not significant. No significant differences in below and aboveground biomass were found between CTPM and PM1 in either freshwater or OSPW. No interaction effect was found between sediment and water treatments in CT sediment types.

In TS sediment types, sediment types had a significant effect on below and aboveground biomass ($p < 0.05$). Water types also had a significant effect on the belowground biomass of *C. aquatilis* ($p < 0.05$). In freshwater, plant below and aboveground biomass in TS was significantly lower than biomass in TSPM and in PM2 ($p < 0.05$). In OSPW, plant aboveground biomass was significantly higher in PM2 than in both TS and TSPM ($p < 0.05$). No interaction effect was found between sediment and water treatments in TS sediment types.

The above to belowground biomass ratio was found to be significantly affected by water types ($p < 0.05$) in both CT and TS sediment types. Although plant aboveground biomass allocation was not different among treatments, plant belowground biomass allocation was significantly lower in OSPW ($p < 0.05$ data not shown). On average, the above to belowground biomass ratio was 0.45 for OSPW and 0.30 for freshwater. Plant sediment types and the interaction of sediment and water had no significant effect on the above to belowground ratio.

3.3. C. aquatilis chlorophyll a fluorescence

Chlorophyll *a* fluorescence statistical analyses indicate significant differences in basic fluorescence parameters among sediment

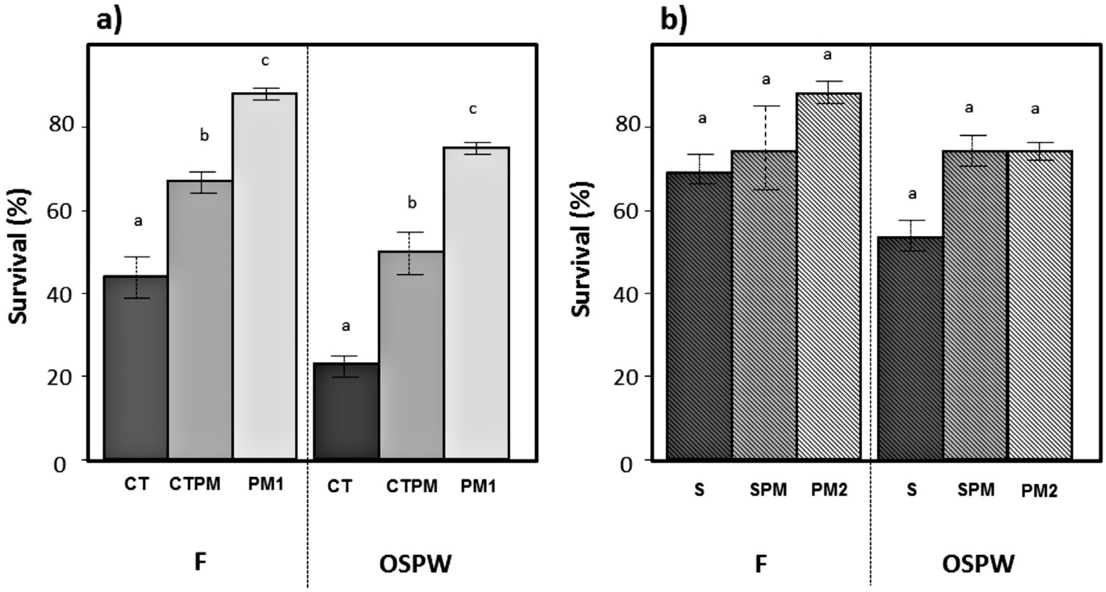

Fig. 1. *C. aquatilis* survival in the two factors experiment (i.e. sediment and water types): the bars represent the averaged percentages ($n = 3$) of *C. aquatilis* survival in each treatment and their associated ±CI (95%). Letters indicate significant differences among sediment treatments following pairwise comparisons using Tukey test. a) CT was statistically compared to CTPM and PM1 while b) TS was statistically compared to TSPM and PM2. Water types had no significant effect on *C. aquatilis* survival. (CT = consolidated-tailings, CTPM = consolidated-tailings and PM mixture, PM = peat-mineral-mix, TS = tailings-sand, TSPM = tailing-sand and PM mixture, F = freshwater, OSPW = oil sands process water).

and water treatments (Fig. 3, Table 5). For plants growing in CT sediment types, sediment had a significant effect on initial fluorescence (F_0) and the slope at the origin of normalized fluorescence rise (M_0) ($p < 0.05$). For plants growing in TS sediment types, F_0, M_0, and ABS/RC were significantly influenced by sediment types ($p < 0.05$).

Overall, basic fluorescence parameters trended higher in OSPW than in Freshwater. Water types had a significant effect on plant performance index (PI), a rough indicator of plant vitality (Strasser et al., 2000) in both CT and TS sediment types ($p < 0.05$). In CT sediment types, *C. aquatilis* growing in OSPW had a significantly higher PI when compared to plants growing in freshwater. In addition, water types had a significant effect on ABS/RC, and ET_0/TR_0 for plants growing in TS sediment types ($p < 0.05$).

4. Discussion

Our study was performed to compare *C. aquatilis* biomass and performance under different sediment and water amendments used by oil sands companies. We have demonstrated that PM amendment to oil sands sediments (CT and TS) significantly increased *C. aquatilis* survival and its ability to accumulate biomass and consequently, its storage of carbon. Our results indicate that despite the improvement of oil sands sediments quality by the addition of PM, OSPW still restricts *C. aquatilis* biomass. We have confirmed that despite oil sands sediments and waters serving as stressors on *C. aquatilis,* its tolerance to oil sands materials makes it a good candidate for the reclamation to a sedge-dominated community in the wet-meadow zones of the post-mined landscape. Even with reduced growth, its survival and gradual accumulation of biomass represents an important ecological contribution to an otherwise low productivity site.

4.1. C. aquatilis is a good plant choice for reclaiming oil sands marshes

Our results provide additional support for speculation of Raab and Bayley (2013) that *C. aquatilis* was a good candidate to reclaim the wet-meadow zones of oil sands created marshes. Although its biomass was significantly affected in the presence of OSPW, tailings and uncapped CT, *C. aquatilis* has shown an ability to tolerate post-mining conditions affected by CT, TS and OSPW. Despite the fact that most transplanted *C. aquatilis* shoots in the CT/OSPW treatment did not survived, approximately 20% of the transplanted shoots established, grew and spread over the two growing seasons. Thus, even in created marshes amended with CT/OSPW, some *C. aquatilis* are expected to survive and increase the likelihood of establishing a sedge-community. If planting *C. aquatilis* is a strategy used to restore CT/OSPW wetlands, changing the transplanting strategy or introducing a higher density of *C. aquatilis* may be necessary to achieve acceptable plant stands and density. Thus, based on *C. aquatilis* ability to survive even in CT, TS and OSPW treatments, establishing a sedge-community in oil sands created marshes is conceivable.

4.2. Sediment and water treatments influence C. aquatilis survival and biomass

Although planting *C. aquatilis* in CT and TS sediments to create vegetated marshes is possible, reestablishing its ability to store carbon that is equivalent to those of natural sedge-communities appears unlikely in the short term. The significantly lower initial survival rate in CT/OSPW indicates that the limiting factor may be the establishment niche of young or stressed plants that have not acclimated to the conditions. The meager below and aboveground biomass of the surviving *C. aquatilis* in CT and TS treatments (in freshwater and OSPW conditions) illustrates the stress exerted by the chemical and physical components of these sediments on plant growth. Compared to PM, both CT and TS contained lower levels of nutrients (carbon, nitrogen and phosphorus) and lower soil moisture content that may thereby explain the compromised below and aboveground biomass measured in CT and TS treatments compared to PM treatments. Trites and Bayley (2009) and Rooney and Bayley (2011) speculated that these sediment characteristics influenced plant community structure in created oil sands marshes. In

Table 4
Summary of the two-way ANOVAs for *C. aquatilis* survival, below and aboveground biomass, and aboveground to belowground biomass ratio in the two factors experiment (i.e. sediment and water types) (CT = consolidated-tailings, CTPM = consolidated-tailings and PM mixture, PM = peat-mineral-mix, TS = tailings-sand, TSPM = tailing-sand and PM mixture).

Sediments compared	Indicators	Sediments (S)		Waters (W)		S x W	
		F value	Pr (>*F*)	*F* value	Pr (>*F*)	*F* value	Pr (>*F*)
CT, CTPM, PM1	Survival	15.40	**<0.01**	5.95	0.09	0.06	0.94
TS, TSPM, PM2	Survival	1.81	0.21	1.71	0.22	0.05	0.96
CT, CTPM, PM1	Belowground biomass	12.73	**<0.01**	19.44	**<0.01**	2.05	0.27
TS, TSPM, PM2	Belowground biomass	14.92	**<0.01**	13.26	**<0.01**	1.05	0.38
CT, CTPM, PM1	Aboveground biomass	4.67	**0.03**	2.01	0.18	2.58	0.12
TS, TSPM, PM2	Aboveground biomass	27.76	**<0.01**	4.31	0.06	1.80	0.21
CT, CTPM, PM1	Aboveground:belowground	1.63	0.24	8.29	**0.01**	0.76	0.49
TS, TSPM, PM2	Aboveground:belowground	1.40	0.30	9.57	**0.01**	0.50	0.62

addition to the sub-optimal conditions of the CT and TS, our analyses demonstrate that OSPW has high salinity content, high level of Na^{+}, Cl^{-}, and naphthenic acids that may exert an additional and significant stress on *C. aquatilis* survival and functions. Although shown to be toxic to *Populus tremuloides* and *Arabidopsis thaliana* (Kamaluddin and Zwiazek, 2002; Pouliot et al., 2012; Leishan et al., 2013), the negative effect of naphthenic acids on emergent macrophytes with inundated roots remains to be demonstrated. Furthermore, little is known about the chemical, physical and biological proprieties of interstitial water in oil sands sediments. The interstitial water may be the key determinant of plant water and nutrient uptake (Young, 1998). This interstitial water can be compromised by freshwater interacting with the oil sands sediments, such as CT, or it can be compromised by the otherwise benign sediments being salinized by the high conductivity of surface water such as OSPW. Logically, CT/OSPW should have both detractors unless CT's detrimental effects on plants decrease over time (e.g. precipitation flushes CT salts) and unless OSPW provides nutrients that may compensate for poor initial conditions.

4.2.1. PM amendments favor C. aquatilis growth in oil sands processed material

Sediment and water types influenced *C. aquatilis* below and aboveground biomass. Hence, materials used for reclamation will influence *C. aquatilis* biomass and if the results can be extrapolated to the stand-level, the restoration of sedge-community functions. In created marshes with CT and TS sediments, *C. aquatilis* biomass was expected to be at its lowest. The use of PM or the mixture of PM with both CT and TS significantly increased below and aboveground biomass by providing sediment with better chemical and physical conditions (i.e. increased access to nutrients, decreased bulk density for better root penetration and increased water-retention

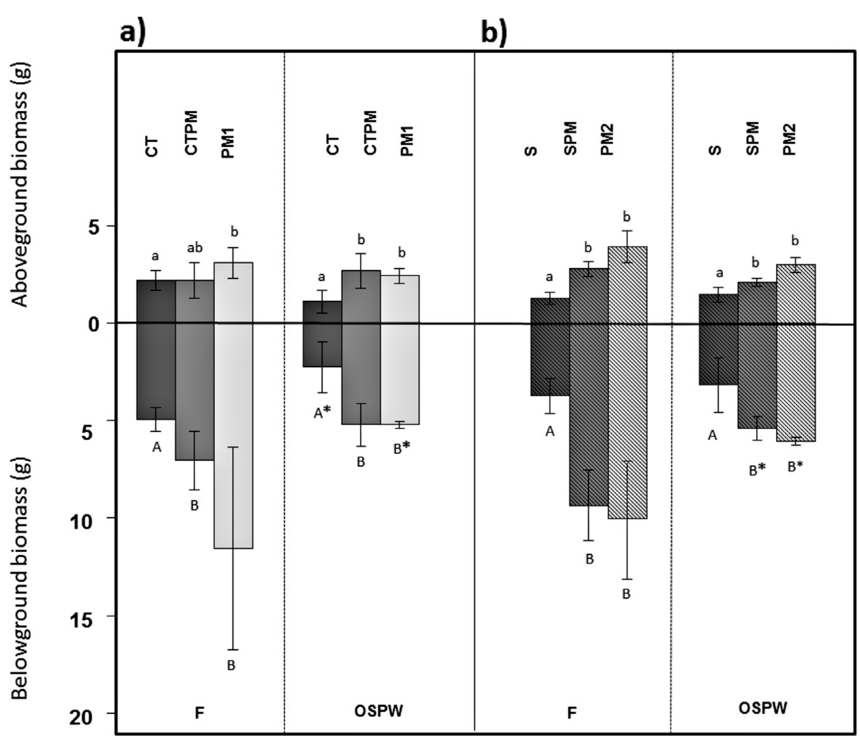

Fig. 2. *C. aquatilis* below and aboveground biomass allocation under a two factors experiment (i.e. sediment and water types). The bars represent the averaged biomass values ($n = 3$) in each treatment and their associated ±CI (95%). Letters indicate significant differences among sediment treatments following pairwise comparisons using Tukey test. (*) is used to indicate the significant influence of water types on *C. aquatilis* belowground biomass. a) CT was statistically compared to CTPM and PM1 while b) TS was statistically compared to TSPM and PM2. Non-capitalized letters represent significant differences among aboveground biomass and capitalized letters represent significant differences among belowground biomass. (CT = consolidated-tailings, CTPM = consolidated-tailings and PM mixture, PM = peat-mineral-mix, TS = tailings-sand, TSPM = tailing-sand and PM mixture, F = freshwater, OSPW = oil sands process water).

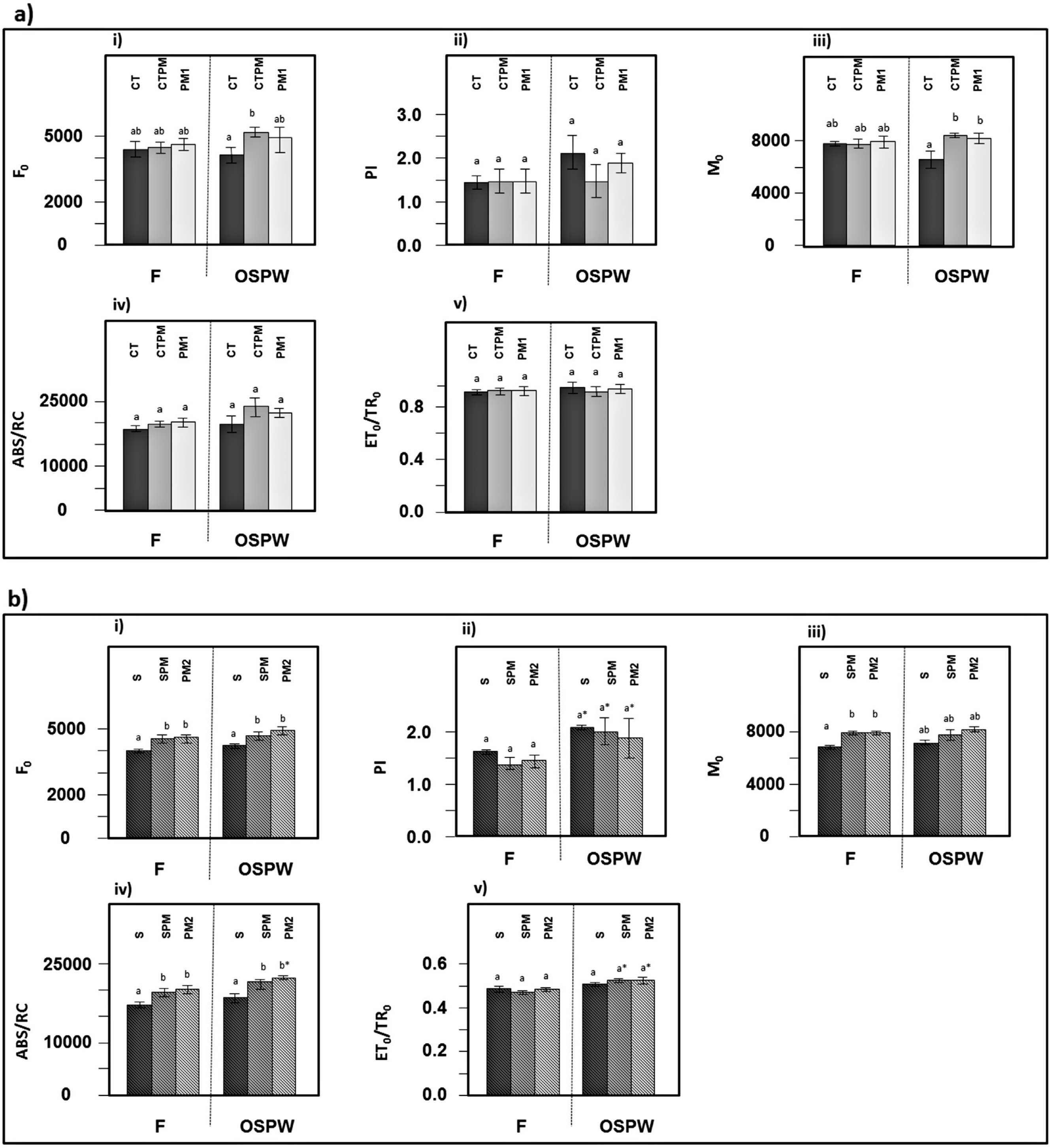

Fig. 3. Derivative chlorophyll *a* fluorescence parameters presenting statistically significant differences ($p < 0.05$). Measurements were taken on *C. aquatilis* growing in different sediments and water treatments: i) initial fluorescence, ii) Performance Index, iii) slope at the origin of normalized fluorescence rise, iv) light absorption per reaction center, v) probability that a trapped exciton moves an electron further than QA. a) CT was statistically compared to CTPM and PM1 while b) TS was statistically compared to TSPM and PM2: Letters indicate significant differences among sediment treatments following pairwise comparisons using Tukey test. (*) is used to indicate the significant influence of water types on *C. aquatilis* derivative chlorophyll *a* fluorescence parameters. (CT = consolidated-tailings, CTPM = consolidated-tailings and PM mixture, PM = peat-mineral-mix, TS = tailings-sand, TSPM = tailing-sand and PM mixture, F = freshwater, OSPW = oil sands process water).

capability). Interestingly, no significant difference in below and aboveground biomass was observed between CTPM and PM1 or TSPM and PM2 (with the exception of plants growing in CT sediment types and freshwater). This result has important implications for oil sands reclamation practices. Indeed, most created oil sands marshes capped with PM have received at least a 50 cm layer of this peat-based sediment. Our results suggest that instead of capping created wetlands with PM, a mixture of PM and oil sand sediments (CTPM and STPM) may be sufficient to optimize marsh sedge-communities biomass (but not survival). Mixing PM with CT and

Table 5
Summary of the two-way ANOVA results for the analyzed chlorophyll *a* fluorescence parameters of *C. aquatilis* submitted to three sediments and two water types (CT = consolidated-tailings sediment type, TS = tailings-sand sediment type). Significant differences are in bold.

Parameters	CT						TS					
	Sediments (S)		Waters (W)		S × W		Sediments (S)		Waters (W)		S × W	
	F value	Pr (>*F*)	*F* value	Pr (>*F*)	*F* value	Pr (>*F*)	*F* value	Pr (>*F*)	*F* value	Pr (>*F*)	*F* value	Pr (>*F*)
F_0	4.17	**0.04**	1.98	0.20	2.02	0.20	4.17	**0.04**	1.98	0.18	2.02	0.17
PI	0.96	0.41	3.00	**0.01**	1.02	0.39	0.57	0.58	7.09	**0.02**	0.20	0.82
M_0	7.98	**0.01**	0.01	0.94	7.76	**0.01**	9.15	**0.01**	0.82	0.38	0.44	0.65
ABS/RC	0.70	0.51	0.45	0.52	0.68	0.52	7.54	**0.01**	5.50	**0.04**	0.13	0.88
ET_0/TR_0	0.49	0.62	0.66	0.43	1.13	0.35	0.12	0.88	6.08	**0.03**	0.48	0.63

TS represents a 33% reduction of PM used and significant financial savings and environmental improvement over current reclamation practices.

4.2.2. OSPW significantly reduced C. aquatilis belowground biomass

The analyses of belowground biomass suggest that the choices of water in the construction of wetlands can significantly influence *C. aquatilis* belowground biomass but interestingly, not its aboveground biomass. The analyses of the above to belowground biomass ratio support these results and indicate that *C. aquatilis* belowground biomass allocation will be reduced in OSPW. Salinity and naphthenic acids content of OSPW are known to directly influence plant physiological function by altering the uptake and transport of water and nutrients from the soil (Kamaluddin and Zwiazek, 2002). Plant roots subjected to OSPW have demonstrated significant physiological changes including cell death in the plant root epidermis and change in the chemistry of parenchyma cells in the root pith (Armstrong et al., 2008). These changes may also result from the indirect effect of naphthenic acids on bacterial communities beneficial to plant functions (Armstrong et al., 2008).

In a striking reversal of our predictions, chlorophyll *a* fluorescence data indicated less favorable habitat conditions in some treatments that involved freshwater or peat amendments than those that involved oil sands by-products. Likewise, plants transplanted in pots filled with tailings sands showed a lower F_0 than plants growing in peat-amended substrates or in peat. F_0 is an indication of photoinhibition and can be high due to photoprotective processes at the level of the light harvesting antenna (Maxwell and Johnson, 2000). Moreover, *C. aquatilis* in OSPW showed healthier photochemical activity (higher ET_0/TR_0, and PI) than plants growing in freshwater treatments. These results may seem counterintuitive; however, chlorophyll *a* fluorescence is sensitive to leaves nutritional status (Huang et al., 2004), suggesting oil sands processed waters positively affect physiological performance, possibly caused by introduced nitrogen compounds in OSPW and CT.

These results reinforce the findings of Mollard et al. (2012) showing that despite growing in tailings-polluted water, *C. aquatilis* can maintain its physiological performance. On the other hand, results indicate that, due to the higher element content of the oil sands by-products, plants subjected to industrial water and substrates may access better nutritional conditions than plants growing on natural substrates and freshwater, an effect that has been shown in other wetland species (Bendell-Young et al., 2000). The role of the above-mentioned better photochemistry activity in leaves of plants affected by industrial by-products on *C. aquatilis* survival and performance is still unclear as can be seen by a lack of positive responses at the whole plant level.

4.3. Reclamation of sedge-community functions at the landscape level

The use of PM amendments can significantly enhance *C. aquatilis* biomass. From a conservative estimation, amending CT and TS sediments with PM can increase the annual biomass production by *C. aquatilis* by a factor of 1.5. If these differences are maintained at the community level, such an increase of biomass becomes a noteworthy landscape improvement. On average, the wet-meadow zone of natural marshes found in the Fort-McMurray region represent approximately 60% of the total marsh area (the open-water zone is 40%) (Roy and Foote, unpublished data). If one quarter (i.e. 10,330 km^2) of the total mineable surface was returned to shallow open water and marsh wetlands (Rooney and Bayley, 2011; Purdy et al., 2005), approximately 6200 km^2 of this area would return to wet-meadows supporting sedge-community dominated by *C. aquatilis*. Based on our estimations (Roy and Foote, unpublished data) and those of Raab and Bayley (2013), natural sedge-communities produce 120–475 g/m^2 of aboveground dry biomass annually. If the reclaimed *C. aquatilis*-community can produce as much biomass as the sedge-community of natural marshes of Fort-McMurray, the total dry aboveground biomass produced annually would range between 744,000 and 294,5000 metric tons across the 6200 km^2 reclaimed. Based on our results, *C. aquatilis* produces approximately 4.7 times more biomass belowground than aboveground. Hence, the combined below and aboveground dry biomass annual contribution for the area to be returned to sedge-community would range between 3 496,800 and 13,841,500 metric tons. Thus, the amendment of PM to CT and TS could make significant revegetation contributions at the landscape scale *C. aquatilis*.

4.4. Management implications

Historically, oil sands marsh reclamation relied on a self-design strategy for plant communities (Harris, 2007). Self-design strategies may not meet reclamation targets if dispersal-limited or low-germinibility plants do not colonize reclamation sites (O'Connella et al., 2013). The scarcity of *Carex* sp. in the oil sands created marshes is believed to be caused in part by dispersal limitations (Trites and Bayley, 2009; Raab and Bayley, 2013). Our study demonstrates that in CTPM, SPM and PM, the introduction of *C. aquatilis* shoots is a technically viable revegetation technique with moderate to high levels of first year survival and very good subsequent establishment and spread on suitable sediment types. *C. aquatilis* shoot introductions can be beneficially used as an early planting strategy in oil sands created wetlands. This revegetation strategy may also occupy sediments historically left unvegetated after oil sands wetland creation, thus, preventing the establishment of less desirable (i.e. invasive, non-native, weedy) plant species observed in many self-designed oil sands wetlands (Raab and Bayley, 2013).

5. Conclusion

Restoring ecosystem structure is more challenging than restoring its functions (Temperton et al., 2004). Although *C. atherodes* and *Carex utricularia* tend to dominate the natural marshes of the Fort McMurray region, our result demonstrate that with the amendment of PM, *C. aquatilis* is a good candidate to reclaim oil sands marsh functions (plant carbon storage). To improve our knowledge of the role of PM amendment in newly created wetlands vegetation, responses across a longer gradient (depth and proportion) of soil amendment should be tested (Sutton-Grier et al., 2009; Ballantine et al., 2012).

The massive challenge of revegetating the post-mined landscape which contain varying levels of contaminants, or natural sediments, and sometimes compromised surface water quality calls for creative combinations of organic amendments (PM) and wise choices of durable, adaptable, late succession plants that can survive, expand and serve as a base of an organic carbon detrital system. Our research confirms that *C. aquatilis* planted in sites supplemented with locally derived peat-based soils is one of the best and most ecologically fitting combinations yet found for widespread wetland reclamation.

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